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Applications of Ultra-High Performance Concrete

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Honors Research Paper

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ABSTRACT

The main objective of this research paper is to determine the current applications of ultra-high performance concrete (UHPC). A second objective is to determine the reason UHPC is used in various applications. More than 17 bridges in the United States have been built with UHPC components. A handful of state departments of transportation have deployed UHPC components within their infrastructure, and many more are actively doing research and considering the use of UHPC. So, this is a relatively new material that is becoming more widely used. The following seven projects, which include UHPC components are discussed in detail: Mars Hill Bridge, Route 624 over Cat Point, Jakway Park Bridge, State Route 31 over Canandaigua Outlet, State Route 23 over Otego Creek, Little Cedar Creek Bridge, U.S. Route 30 over Burnt River.

The enhanced durability properties facilitate a lengthening of design life and allow for UHPC to be used as a thin overlay for bridge decks. The enhanced strength of UHPC allows for redesign of concrete beams. The enhanced strength and development length reduction allow for UHPC to be used to connect precast concrete elements together. Another objective of this research paper is to determine potential future applications of UHPC. Research has been done to determine the suitability of UHPC being used for drill bits, sewer pipes, precast spun concrete columns, piles and precast tunnel segments.

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1. INTRODUCTION

Ultra-high performance concrete (UHPC) is defined as a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement [1]. Conventional concrete has a water-to-cementitious materials ratio that is generally between 0.4 and 0.6 and contains no discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 21.7 kilopounds per square inch (ksi) or 150 Megapascals (MPa) and sustained postcracking tensile strength greater than 0.72 ksi or 5 MPa. Conventional concrete generally has a compressive strength less than 8 ksi. UHPC has a discontinuous pore structure that reduces the amount of liquid that enters the concrete, significantly enhancing durability compared to conventional and high-performance concrete.

The extra strength of UHPC provides many benefits, but has a higher cost than conventional concrete. The objective of this paper is to examine when UHPC has been used and to determine how the benefits outweigh the extra cost. UHPC can allow for quicker construction of bridges, which can be a benefit that outweighs the cost.

There has been research conducted on UHPC for use in a variety of applications. These applications include precast concrete piles, seismic retrofit of substandard bridge substructures, thin-bonded overlays on deteriorated bridge decks, and security and blast mitigation applications [2]. In a general sense, UHPC has proven to be a practical solution where using conventional concrete is not sufficient. For example, connections with conventional concrete have hindered the use of prefabricated elements, while field-cast UHPC allows for a redesign and simplification of connections of prefabricated elements while simultaneously increasing long-term durability and construction speeds.

The cost to produce UHPC is much greater than the cost to produce the same amount of conventional concrete [3]. Consequently, applications have focused on reducing concrete member thickness, changing concrete structural shapes, or developing solutions that address shortcomings with existing non-concrete structural materials. Structures built with UHPC are expected to have a longer service life and to be maintained less often than structures built with conventional concrete.

A life cycle cost analysis was conducted for two replacement methods for the Eder bridge in Felsberg, Germany [3]. The first method was precast UHPC box girders filled with lightweight concrete. The second method used conventional prestressed concrete bridge members. Although the UHPC had higher initial costs, the predicted life cycle cost over 100 years would be less for the UHPC bridge.

2. OBJECTIVES

The main objective of this research paper is to determine under what conditions the benefits of UHPC outweigh the extra cost. Different published papers were examined in order to determine current applications of UHPC. Some of these examined papers were reports on bridges built with UHPC components. By researching the current applications of UHPC, the benefits that UHPC provides can be deduced. This would allow an engineer to know in what applications using UHPC is beneficial.

Published research papers on potential applications were also examined. Engineers are constantly coming up with better solutions. One published research project explained how UHPC could potentially be used for piles instead of steel. This is an example of a research project illustrating that UHPC could provide a better solution to a problem where UHPC is not currently used. This would allow an engineer to consider using UHPC to solve a problem where UHPC is not the conventional solution.

3. UHPC BRIDGE DECK OVERLAY

The first U.S. deployment of UHPC as a bridge deck overlay was completed in May 2016 on a reinforced concrete slab bridge located in Brandon, Iowa [4]. The primary difference between typical UHPC formulations and UHPC mixes that have been specially formulated for overlay applications are the rheological properties. Most UHPC mixes are formulated to flow under the force of gravity and be self-consolidating. UHPC mixes formulated for overlay applications are typically thixotropic. Thixotropy is a time-dependent shear thinning property of a non-Newtonian fluid, which causes a material to remain solid-like under static conditions and to flow when agitated or sheared. Since bridge decks are not level, if a typical UHPC mix were to be used as a bridge deck overlay, it would flow from the high side to lower points on the structure, which would cause difficulty with screeding and profiling when constructing the bridge deck overlay.

3.1 Advantages

UHPC has mechanical and durability properties that make it a well-suited candidate for concrete bridge deck overlays [4]. UHPC has a very low permeability and very good resistance to damage from freezing and thawing. Thus, there is a reduced chance of water or contaminates entering the concrete and causing damage from a freeze thaw cycle, which enhances durability. The potential for rutting is reduced because UHPC has increased abrasion resistance. Rutting is an important pavement distress to reduce because rutting affects the ride-ability, integrity and safety of a pavement. Rutting is a common cause of vehicles hydroplaning on the pavement surface. Compared with conventional concrete, an appropriately designed UHPC mix will exhibit relatively low shrinkage, which reduces the potential for shrinkage-induced cracking. Also, the internal microfiber reinforcement in UHPC mixes would reduce the width of shrinkage-induced cracks compared to conventional concrete. So, using a UHPC mix will reduce the width and quantity of cracks on the surface of the bridge deck.

UHPC has high strength and high stiffness. Thus, a thin layer could provide both enhanced durability and increased strength with a slight reduction in dead load [4]. Traditionally, rigid concrete overlays range in thickness between 2.5 inches (51 mm) and 6 inches (152 mm), which corresponds to dead loads between 30 psf (1.4 kN/m^2) and 75 psf (3.6 kN/m^2). Overlays constructed with UHPC have had a thickness between 1 inch (25 mm) and 2 inches (51 mm), which corresponds to dead loads between 13 psf (0.57 kN/m^2) and 26 psf (1.2 kN/m^2).

3.2 Bonding

Having a bonded overlay achieve and maintain a good bond with the existing concrete on the bridge deck is critical. A study was conducted at the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) to investigate the bonding between UHPC and existing concrete [4]. The UHPC tested had thixotropic properties because this helps with the construction of the overlay. The purpose of this research was to determine the tension bond strength of a UHPC overlay to a substrate and compare that bond strength to that of a commonly used overlay material, latex modified concrete (LMC).

Tests were conducted on different substrate materials using different substrate surface preparation methods [4]. The substrate materials that were tested were conventional concrete and UHPC. Both UHPC and LMC overlays were tested with the substrate surface prepared using both scarification and hydrodemolition. The bond strength was tested using the direct tension pull-off bond test based on ASTM C1583. The tests indicated that UHPC overlays resulted in comparable, if not higher, bond strengths than LMC overlays, except for the case where a scarified concrete substrate was used. The results indicated that bond strengths tended to be higher if a UHPC substrate was used, rather than a conventional concrete substrate. Finally, the hydrodemolition surface preparation technique offers the possibility of obtaining higher bond strengths than scarification. This is attributed to the fact that mechanical preparation methods may cause microcracking on the substrate material, which may eventually increase the bond performance.

The laboratory investigation resulted in comparable, if not better, bond performance of UHPC overlays compared to that of LMC overlays, making it possible to consider the potential use of UHPC overlays in bridge decks [4]. It can also be concluded that the substrate material used influences the bond strength, as the UHPC substrate exhibited higher bond strengths than concrete substrates. Likewise, the substrate surface preparation method seems to be a factor in obtaining an adequate bond. The substrate surfaces treated with hydrodemolition achieved higher bond strengths than those obtained on a scarified substrate surface.

The first U.S. deployment of UHPC as a bridge deck overlay was finished in May 2016 on a reinforced concrete slab bridge located in Brandon, Iowa [4]. A field inspection determined that isolated delaminates may be present in the deck a few months after the UHPC overlay was constructed. Thus, there was a necessity to assess the bond between the UHPC overlay and substrate concrete. In November 2016, a field study was conducted to determine the condition of the bond between the UHPC overlay and the substrate concrete bridge deck.

Based on the observations and data collected during that field study, it can be concluded that the bond between the UHPC overlay and the existing concrete bridge deck was intact [4]. Mechanical testing determined that the locations suspected of having good UHPC bonds had the capacity to carry relatively high tensile stresses without bond failure. The field test also showed that good bonding was achieved even at locations where deck concrete was not roughened prior to placement of the UHPC overlay; however, this is dependent on the surface quality of the substrate concrete and is not a recommended practice. The two test locations suspected of delamination were indeed found to have delaminated concrete. However, the delamination was already existing within the deck concrete and was likely present prior to placement of the UHPC overlay.

Visual inspection of the UHPC field specimens' interface indicated that the interface between the UHPC overlay and deck concrete appeared intact [4]. This was further investigated through microstructural analysis by examining the interface with a scanning electron microscope. The results of the Microstructural analysis suggested that there was a high density of UHPC in direct contact with the concrete substrate surface. This high density was caused by the high content of hydration products from the UHPC and low porosity on the surface of the interface. The consequence of this was a large amount of direct contact between the UHPC overlay and the conventional concrete surface, which would result in a high tensile strength of the interface.

Thixotropic UHPC overlays can develop adequate bond strength to substrate concrete if good overlay consolidation can be achieved with a percentage of interface voids below 10% [5]. If this condition is satisfied, then the concrete surface roughness becomes less of a factor in developing adequate direct tension bond strength. However, if adequate consolidation cannot be achieved, some degree of surface roughness would be necessary to develop adequate bond strength. Surface roughness is critical for composite action and horizontal shear transfer. Thus, surface roughening is highly recommended.

3.3 Costs

The cost of UHPC is usually more than most highway bridge construction materials [4]. Furthermore, the material cost and bid line item cost for UHPC can vary significantly. Appendix A provides a comparison of the approximate cost of various overlay solutions. The UHPC costs shown in Appendix A only reflect the cost of the material and does not include the cost for installation, and thus, they appear relatively low. Generally, UHPC overlays in the United States would likely exceed the cost of most traditional overlay solutions until the technology becomes more widely used. In Switzerland, UHPC overlays are being more commonly constructed, and therefore, the costs are becoming more competitive. Appendix A includes the approximate cost of a UHPC overlay on the Chillon Viaduct bridge in Switzerland, which is comparable to the more expensive conventional solutions in the United States.

4. PAIRING PREFABRICATED ELEMENTS WITH UHPC CONNECTIONS

Structural connections have to perform at least as well as the rest of the structural components of the bridge. Conventional connections with prefabricated bridge elements have proved to be difficult to fabricate, difficult to install, expensive, and susceptible to underperformance [6]. The superior mechanical properties of UHPC are able to solve some of these issues and allow for far superior field-cast connections. The mechanical properties of UHPC allow for redesign of common connection details in ways that promote both ease and speed of construction [7].

The increase in tensile strength is the fundamental reason why UHPC is superior in use for connections [6]. The tensile strength is increased due to the high load of fiber reinforcement and the cementitious matrix of the UHPC.Since UHPC has a higher tensile strength, the resistance to tensile splitting and pullout in concrete connections is significantly increased. UHPC is rapidly being adopted as a field-cast material that addresses longstanding bridge construction needs and that outperforms conventional solutions. Fourteen states and four Canadian provinces have already begun using this technology, and use is expected to continue to grow over the coming years as it becomes a common state-of-the-practice solution. UHPC used in connections with prefabricated bridge elements is demonstrating that it can be implemented in ways that deliver enhanced performance for future generations of the traveling public.

4.1 Common Connections

The most common connection utilizing UHPC is a reinforcing bar lap splice arrangement [6]. The reinforcing bar lap splice arrangement is used to connect prefabricated concrete bridge deck panels, the top flanges of decked girders, the backwalls of prefabricated integral abutment elements, and even pier columns to caps. Reinforcing bar lap splice connections have proved to be cost effective to fabricate and easy to assemble in the field. These connections need little embedment length and no specialized anchorage. Research has indicated that uncoated and epoxy-coated reinforcement can be developed beyond the bar yield strength when the embedment length is only eight times the bar diameter. This results in non-contact lap spliced connections for No. 5 bars that might only be 6 inches wide and will not require post tensioning, headed bars, hooked bars, lacer bars, or any other specialized anchorages. Field-cast UHPC can also be used for shear connections between bridge decks and supporting girders, for headers at expansion joints, for link slabs over piers in multi-span structures, and for seismic retrofits of substandard lap splices in conventional reinforced concrete substructures.

UHPC also can create an exceptional interface bond to precast concrete, decreasing the probability of water entering the structure [6]. The enhanced bond is attributed to the low percent of voids in UHPC and combined with the increased tensile strength, but the surface of the precast concrete element must be properly prepared in order to reach a high bond strength. Most commonly, this preparation includes the creation of surface texture through the use of a paste retarder to create an exposed aggregate surface along with prewetting to reduce the dryness of the field-cast UHPC adjacent to the interface.

5. ADJACENT BOX BEAM BRIDGES

Adjacent box beam bridges are commonly used in North America for short and medium length bridges, but this bridge design has a common problem, which is the shear key connection deteriorates over time [8]. This leads to an inadequate overall performance of the structure. Full-scale structural testing has been conducted to compare conventional grout connections to UHPC partial and full depth connections of adjacent box beams. Figures 1 and 2 illustrate a partial-depth UHPC connection and a full-depth UHPC connection.

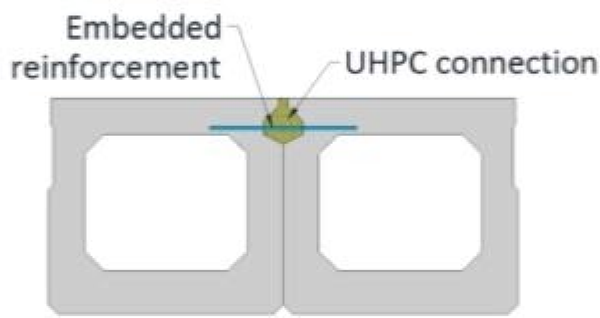

Figure (1) Partial-depth UHPC Connection [8]

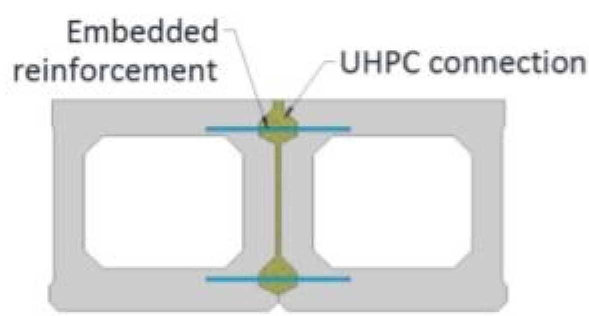

Figure (2) Full-depth UHPC Connection [8]

The beams in this study were subjected to 10 cycles of thermal loading and millions of cycles of structural loading [8]. The results of the study showed the behavior of the adjacent box beam bridges with UHPC connections could be expected to be comparable with an equivalent structural system with no field-cast connections. Differential deflection between adjacent beams can be an indicator of the serviceability performance of a connection. Based on the tests in this study, the differential deflections for the UHPC connections were below 0.005 inch (0.127 mm). The Precast Prestressed Concrete Bridge Design Manual limits differential deflection between adjacent box beams to 0.02 inch (0.51 mm) for spans up to 100 ft (30.5 m). Hence, the UHPC connections would meet the serviceability requirements.

The mechanical capacity of the UHPC connection was observed to increase connection capacity so that, under the application of large transverse tensile stresses, tensile rupture occurred within the precast concrete box beams [8]. This indicates that the UHPC connection has a higher tensile strength than the concrete box beam. So, the box beam would not fail due to the connection in tension. The results showed that the full-depth connections had marginal improvements in load distributions over the partial depth connection. This is likely due to the increased depth of the connection, which significantly increased the transverse flexural and shear stiffness of the connection. However, increasing the depth of the connection increases construction costs and possibly construction complexity. A partial-depth UHPC connection appears to be sufficient to achieve the performance requirements.

6. DEVELOPMENT AND LAP LENGTH REDUCTION

The development length of reinforcements embedded into UHPC can be significantly shorter than the development lengths of conventional concrete [9]. Shortening the development length of prestressing strands can allow engineers to change the design of some structural systems, including spliced girder and continuous-for-live-load bridges. UHPC, when used in field-cast connections between prefabricated bridge elements, can create robust connections that are comparable to single piece elements.

Research was conducted to determine the lap splice length of untensioned prestressing strand in field-cast UHPC [9]. The results suggest that, for the steel fiber reinforced UHPC, the 0.5-inch (12.7-mm) diameter strands can be fully developed within 20 inches (0.51 m), and the 0.6-inch (15.2-mm) diameter strands can be fully developed in approximately 24 inches (0.61 m). The 0.5-inch (12.7-mm) diameter strands can be fully developed in the PVA fiber reinforced UHPC in approximately 36 inches (0.91 m). In all cases, greater or lesser confinement of the strands would result in changes in the development length. Confinement parameters of interest include the following: cover, fiber reinforcement type, volume, efficiency, passive transverse reinforcement and concrete tensile response.

7. COMPLETED PROJECTS WITH UHPC COMPONENTS.

There have been over 17 completed projects in the United States with UHPC components [10]. Appendix B lists 17 projects that were completed between 2006 and 2012 within the United States that have UHPC components. The following seven projects are discussed in detail: Mars Hill Bridge, Route 624 over Cat Point, Jakway Park Bridge, State Route 31 over Canandaigua Outlet, State Route 23 over Otego Creek, Little Cedar Creek Bridge, U.S. Route 30 over Burnt River.

7.1 Mars Hill Bridge in Wapello County, Iowa

In 2003, Wapello County, Iowa and the Iowa Department of Transportation were granted funding for a project utilizing UHPC [11]. UHPC will be used in pretensioned, prestressed concrete beams in this bridge replacement project. The beams will be pretensioned using 0.6-inch diameter low relaxation strands. No mild reinforcing steel, except an amount to provide composite action between the beam and cast-in-place deck, will be used. To verify shear and flexural capacity of the beam, 10-inch and 12-inch shear beams and a 71-foot long test beam have been cast. Testing was completed at Iowa State University and the Center for Transportation Research and Education (CTRE) in Ames, Iowa. The service capacity under flexure had been verified by testing, and casting of the 111-feet production beams started on June 26, 2005.

CTRE, Wapello County, and the Iowa DOT Office of Bridges and Structures jointly designed the test beam, production beams, and plans for the bridge [11]. A modified Iowa 45-inch bulb tee was used. To save material in the beam section, the web width was reduced by two inches, top flange by one inch, and the bottom flange by two inches. Because of the research on UHPC conducted by FranzJosef Ulm of the Massachusetts Institute of Technology, he provided a final review of the beam design.

The design of the beam was a challenge for the staff involved because of lack of approved specifications [11]. Design guidelines have been developed by France, and design recommendations were available from reports. However, there are no specifications currently available in the United States. A review of the service and ultimate strength checks recommended by the French design guide and the research model developed by Dr. Ulm were used as a guide for design. The following additional design data was also used: a release compressive strength of 14,500 psi, a release modulus of elasticity of 5,800 psi, a final design compressive strength of 24,000 psi, a final modulus of elasticity of 8,000 psi, an allowable tension stress at service of 600 psi, an allowable compression stress at service of 14,400 psi, LRFD HL-93 loading and Grillage analysis for distribution factors.

The final beam design section used forty-nine 0.6-inch strands stressed to 72.6% of ultimate [12]. To reduce the stresses and the end of the beam, five strands were draped along with debonding. The 71 foot test beam used an identical strand layout to verify release stresses. The dimensions of this test beam are shown in Figure 3.

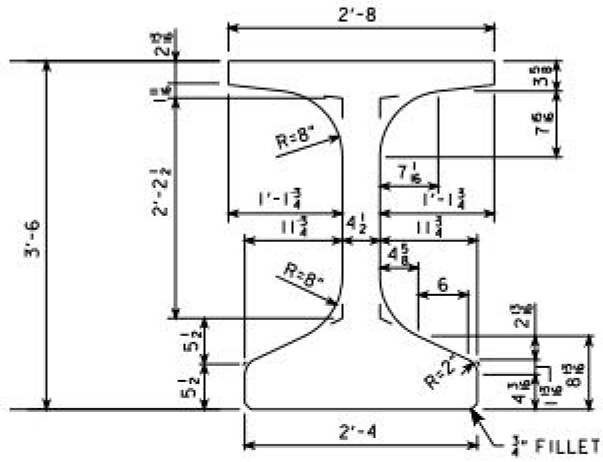

Figure (3) Dimensions of Test Beam [11]

In addition to designing lighter weight beams with more slender cross sections and no reinforcement, this revolutionary concrete provides an added advantage in that it is highly impermeable, thereby reducing the threat of corrosion within the structure. This should increase lifespan for bridges subjected to moisture and the effects of road salt.

This project represents only the start of the use of this UHPC system in bridge designs, which could change the way bridge engineers approach designs, argues Vic Perry, Vice President and General Manager for Ductal at Lafarge North America [12]. Vic Perry believes it will be possible to build an entire bridge, including the deck, without reinforcement. This bridge represents a step towards it being a reality. UHPC provides real opportunities within the prestressed concrete industry. The material also provides an opportunity to create slender, long-span beams and lighter bridges without the need for reinforcing bars.

Another key advantage was the speed with which the bridge was completed after the testing was verified [12]. Casting the 110-ft-long beams was completed in July of 2005, and construction began in August. By the following February, the bridge was opened to traffic. The beam spacing was 9 ft 7 inches, with 4-ft overhangs, creating a 24-ft 6-inch wide completed structure.

There is a tremendous potential to improve cross sections [12]. The use of steel fibers and the elimination of reinforcement allow for use of a dense material without the concerns of corrosion. Engineers associated with this project believe that there is a realistic possibility to create an entire bridge, including the deck, with UHPC. The successful Mars Hill Bridge project has the team of engineers that designed the bridge determining which projects can take advantage of this system. The team of engineers determined a bridge in Buchanan County in Iowa would benefit from this system.

7.2 Route 624 over Cat Point Creek, Richmond County, VA

Virginia Department of Transportation (VDOT) used five 45-inch tall bulb tee beams with UHPC in the bridge on Route 624 over Cat Point Creek [13]. The bridge has ten 81.5 ft spans. One of the spans contained UHPC beams. The steel fibers provided adequate shear resistance, so the UHPC beams did not contain stirrups normally used in conventional concrete, but there is confinement steel at the beam ends.The specified minimum 28 day compressive strength was 23 ksi and the specified maximum water to cementitious material ratio was 0.2. UHPC with high strength and very low permeability was used in five beams in one of the 10 spans of the bridge.

Research was conducted to evaluate the use of UHPC in the Route 624 Bridge. The objectives of the research were the following: evaluating the material properties of the UHPC, testing a test beam to failure, measuring strains in beams and noting any deck cracking [13]. The results of the study indicated that the use of the UHPC led to very high strength and high durability attributable to a very low water to cementitious material ratio, low permeability, high resistance to cycles of freezing and thawing, and very tight cracks under load, which should provide for a much longer service life compared to the use of conventional concrete. The study recommends that UHPC be considered for use in closure pours and beams with optimized cross sections.

The results of the study showed that the reinforcement difference over the bents did not seem to result in a different cracking pattern [13] .Over the bents of the bridge the reinforcement varied between different combinations of number 4, 5 and 6 bars. The cracking pattern on either side of a bent and among different bents indicated a different number of transverse cracks. Even the same reinforcing pattern did show a difference in the number of cracks.

The difference in beams did not reveal significant differences in the cracking pattern at the time of the survey [13]. However, the UHPC beams had a higher coefficient of thermal expansion (CTE) than those of the other concrete beams. The CTE of UHPC is typically between 6.6×10^{-6}/°F and 8.3×10^{-6}/°F. The CTE of UHPC is considerably higher than the CTE of conventional concrete, which is typically around 5.5×10^{-6}/°F and could affect the cracking severity with time. Future performance evaluations would provide more insight into the cracking severity and its effects.

VDOT using UHPC is not practical because of its high cost [13]. The use of UHPC beams can extend longevity. However, the casting of these beams requires extra attention in preparation and the materials used are proprietary and expensive, leading to a net cost increase in production. In this application, the contract unit price of the UHPC beams was more than five times the cost of the HPC beams. However, there were few UHPC beams, and this was the first application of these beams in Virginia. In certain applications, the higher cost may be justified because of the improved properties, extending service life with minimal or no maintenance. More efficient shapes, design requirements, and material and construction specifications need to be developed to make the use of UHPC practical.

VDOT should support further research to evaluate the use of UHPC with fibers in closure pours because of the tight cracking pattern that would hinder the penetration of aggressive solutions [13]. Tight cracks with widths less than 0.1 mm hinder the penetration of aggressive solutions and provide longevity. This could potentially decrease the lifecycle cost.

7.3 Jakway Park Bridge, Buchanan County, IA

The new Jakway Park Bridge in Buchanan County, Iowa, is a great example of expanding the use of UHPC in bridge girders and specifically in the new Pi girder [14]. Engineers can take better advantage of the properties of UHPC and help reduce costs in future projects by understanding the design process of the second generation Pi girder and leveraging its full capabilities. Officials in Buchanan County were granted funding through the Innovative Bridge Research and Construction Program (IBRC), managed by the Federal Highway Administration, to construct a highway bridge using an optimized Pi-girder section with UHPC. The design of the second generation Pi-girder section, provides the first application of the Pi section for a highway bridge in the United States. The girders are pretensioned longitudinally and tied together transversely with mild reinforcing steel and steel diaphragms.

Buchanan County and Iowa Department of Transportation were given the opportunity to build on that UHPC experience with this project [14]. The same UHPC mix was used to fabricate five optimized Pi girders. Two of the Pi girders were 25-ft long girders reserved for testing at the Federal Highway Administration’s (FHWA) Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia. The other three girders were 51-ft long and used for the bridge construction.

The replacement bridge, 115-ft 4-inch long by 24-ft 9-inch wide, is located on a county road in a northeast section of Buchanan County over the east branch of Buffalo Creek [14]. The UHPC component is the center span, which is 51 feet and 2 inches in length. The 50-ft long simple-span Pi sections are supported on plain neoprene bearing pads. The beam ends are encased in cast-in-place diaphragms with 3.5 ksi compressive strength concrete. End spans consist of traditionally reinforced cast-in-place concrete slabs with integral abutments supported on steel HP10x42 piles. The pier caps are supported on steel piles encased in concrete.

As a starting direction, the design team used the initial optimized first generation Pi shape, which was developed by the TFHRC and the Massachusetts Institute of Technology [14]. The first generation Pi shape was created to optimize the UHPC mix by minimizing the cross section and taking advantage of the material properties for the bridge deck. Testing of the section by TFHRC had revealed stresses that exceeded the transverse capacity of the deck and a low transverse live load distribution between adjacent Pi sections. These two issues were the biggest design challenges for the project and suggested that improvements to the initial Pi-girder section would need to be made.

Load testing at TFHRC showed that the 3-inch thick deck under service load did not have the strength to meet the design specifications for a 12.5 kip tandem or single 16 kip wheel load with 33% impact included [14]. Improvements to the section were investigated by the Iowa DOT and Iowa State University and included finite element analysis of the different modifications. Improvements to the first-generation Pi section were initially investigated, with the intention of reusing or modifying the existing forms. Several design options were considered for strengthening the deck. These included increasing the deck thickness with or without reinforcement, adding ribs under the deck with or without mild reinforcement or post-tensioning, and thickening the deck with or without reinforcement.

After review, the design team decided to use a uniform 4-inch thick deck with transverse post-tensioning [14]. This kept the changes as simple as possible and attempted to keep the cost of modifying the beam forms within budget limits. The connection detail that was used in the initial test consisted of a grouted keyway with horizontal tie bolts provided at 3-ft spacing. To improve load distribution and help stiffen the section, two adjustments were made. Steel diaphragms were added at the quarter-span points across the bottom flange, and grouted, pockets containing No. 8 reinforcing tie bars were provided at 18-inch spacing.

Due to the high costs of upgrading and modifying the forms, the sole fabricator interested in casting the modified Pi sections delivered a bid that was too high for the budget [14]. FHWA officials at TFHRC suggested that further revisions be made to the first-generation section and new forms be created for a second-generation Pi girder. The FHWA agreed to fund the forms and purchase two test beams for evaluation. The three production beams would be purchased at the same time to reduce setup and casting costs for all of the beams. In addition, the revised section would be available for use on future projects by other state agencies.

Four more changes were made to finalize the second generation Pi girder [14]. First, two types of fillets, 5 inches and 8 inches deep, were added at the connection between the web and deck to improve concrete flow during placement and to stiffen the slab section. Second, the interior deck thickness between the webs was increased to 41/8 inches to reduce service load stresses. Third, the web spacing was reduced by 4 inches to provide a more balanced spacing of the webs for the three beam cross section and to reduce service load stresses. Finally, the post-tensioning was removed from the deck. Due to the lack of test data on the revised section, number 5 reinforcing bars at 1-ft centers were included in the deck. Figure 4 displays the design of the second generation Pi Girder that was constructed in the Jackway Park Bridge

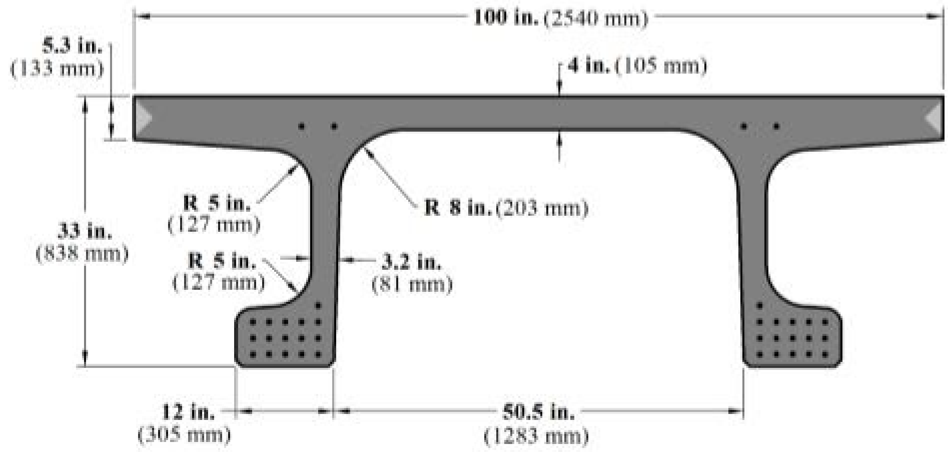

Figure (4) Pi Girder in Jackway Park Bridge [10]

Typically, high-speed pan mixers are used because of the large amount of time and energy needed to thoroughly mix the concrete [14]. In this case, ready-mixed concrete trucks were used for mixing the required 21,500 psi design compressive strength. As the material's performance is affected by the alignment of the steel fibers, a horizontal bucket almost as wide as the form was fabricated to place the material so it would flow freely along the form and properly align the fibers.

7.4 State Route 31 over Canandaigua Outlet, Lyons, NY

The purpose of the State Route 31 over Canandaigua Outlet bridge project was to replace the superstructure on a former steel jack-arch bridge while retaining most of the cast-in-place abutments [15]. The new bridge consists of a single-span, 87 ft 5 inches long and 42 ft 9 inches wide, comprising eight precast concrete deck bulb-tee girders that are 41 inches deep. The interior girders have a top flange that is 4 ft 10 inches wide while the width of the exterior girders' top flange is 5 ft 1 inch in length. The flange is 6 inches deep at the edges. This top flange and the joint design represented the innovative aspect of this bridge technique for the project.

To complete a bridge superstructure replacement project on a tight deadline, officials at the New York State Department of Transportation (NYSDOT) decided to use a new design of conventional bulb tee girders [15]. To overcome durability concerns of using conventional deck bulb tee girders, customized bulb tees were designed to create joints between the girders that would be filled with UHPC, optimizing the system. The result was a satisfactory design with a significantly shorter construction time and may be used in additional applications.

NYSDOT engineers were familiar with the deck bulb tee, but were concerned about the fatigue of the longitudinal joints loaded by heavy traffic [15]. NYSDOT engineers have seen it used in low-traffic applications, but this bridge already has fairly high usage, and NYSDOT engineers are preparing for the future when traffic increases further. By using the customized bulb tees, NYSDOT engineers are reducing inspection and maintenance costs while avoiding worries about leaks or corrosion.

The joints were overfilled by a few millimeters to ensure they would be level when settling was completed [15]. The excess was later grounded off. This process is shown in figure 5.

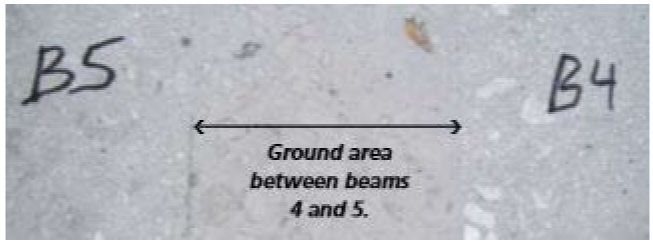

Figure (5) Ground Area Between Beams [15]

UHPC is a very high-end concrete with very high-strength capabilities, and it will resist scaling, freeze-thaw deterioration, and cracking due to the high steel fiber content [15]. The importance of UHPC in this project was not the added strength, but the speed with which the construction could be completed. The shorter length of reinforcing bar allowed for a narrower joint that could be completed in less time.

As a first-time use, costs were somewhat higher as expected, due to the learning curve associated with the new techniques [15]. The steep learning curve and costs will be reduced as NYSDOT and contractors become more familiar with the new techniques. NYSDOT eliminated the costs associated with later inspections and maintenance, which become significant, so the long-term value is higher.

7.5 State Route 23 over Otego Creek, Oneonta, NY

The Route 23 over Otego Creek bridge project used UHPC in joints between precast, prestressed concrete full depth deck panels [16]. The project was completed in 2009. UHPC joints eliminated the need for the commonly used longitudinal post tensioning of the deck panels. Precast concrete decks with UHPC joints and haunches are an alternative to cast-in-place decks for some of NYSDOT's bridge replacement projects.

NYSDOT is at the forefront of developing enabling technologies for accelerated bridge construction (ABC) [16]. The use of precast concrete bridge elements is an efficient way to accelerate bridge replacements, but the durability of the joints between the members is a concern. NYSDOT, with the assistance of the Federal Highway Administration and the concrete industry, has developed and tested joints using UHPC. These joints need only be 6 inches wide since the reinforcing bars up to size number 6 can be fully developed within a joint of that size. These joints are also highly durable and crack resistant. The first use of the UHPC joint was for the superstructure for Route 31 over Canandaigua Outlet in Lyons, N. Y. With a short schedule, this project used deck bulb tees with UHPC joints between them.

7.6 Little Cedar Creek, Wapello County, IA

In the fall of 2011, Wapello County, Iowa, used UHPC two-way-ribbed, modular deck panels (waffle panels) and UHPC field-cast, continuity connections to construct the Little Cedar Creek Bridge [17]. All connections from panel to panel and from panel to beam used UHPC. The bridge consists of 14 waffle panels. The panels are 15 ft long, 8 ft wide, and 8 inches deep, with the top flange portion of the waffle panels only 2.5 inches thick. The waffle panels sit on conventional precast, prestressed concrete I-beams, 39 inches deep, spanning 63 ft. The bridge is 32 ft 2 inches wide. The panels are connected to the beams by reinforcement extending from the beams into the space between the ribs of the panels and the tops of the beams. UHPC is poured around this reinforcement.

This bridge was a first of its kind and was proven very successful. The design of the bridge and initial testing was by the Iowa Department of Transportation [17]. The design was relatively straightforward and utilized the unique properties of UHPC. Production of the panels was by Coreslab Structures Inc. in Omaha, Nebraska, and was completed with ease, with very few adjustments to existing technologies or processes. The UHPC was furnished by Lafarge North America Inc. Construction moved quickly due to the use of the modular panels and readily available equipment, materials, and techniques. The UHPC field casting process was new to the contractor, Bloomfield Bridge & Culvert, and required some additional early instruction, but the process went quickly and smoothly.

Overall the Little Cedar Creek Bridge project was a huge success exceeding all expectations of Wapello County [17]. This project is an example of how UHPC can change the way bridge decks are constructed and can significantly extend the service life of highway infrastructure in this country. Wapello County engineers believe that UHPC has not only performed well in this project but shows great promise for innovation in the future.

7.7 U.S. Route 30 over Burnt River and UPRR bridge, Oregon

The design of the U.S. Route 30 over Burnt River bridge was challenging because design guides and specifications for UHPC have not been formally developed and published [18]. Current research is working toward published specifications. Hence, the precast prestressed UHPC deck panel connections used for this project are based on recent FHWA research and testing. The precast deck panels, precast girders and bridge substructure were designed by traditional methods according to the Fifth Edition of the AASHTO LRFD Bridge Design Specifications, PCI Precast Prestressed Concrete

Bridge Design Manual and Oregon Department of Transportation Bridge Design and Drafting Manual.

Based on FHWA research, the longitudinal epoxy coated number 5 mild steel deck reinforcement in the transverse panel to panel connections can be fully developed in less than six inches with steel fiber reinforced UHPC [18]. For field applications, FHWA recommends a 6-inch bar lap as a practical minimum. In order to develop the longitudinal deck bars and sufficiently connect the precast panels, a UHPC design strength of 14.0 ksi in 14-days and 17.0 ksi in 28 days were required for this project. Figure 6 details the UHPC joint used on this project.

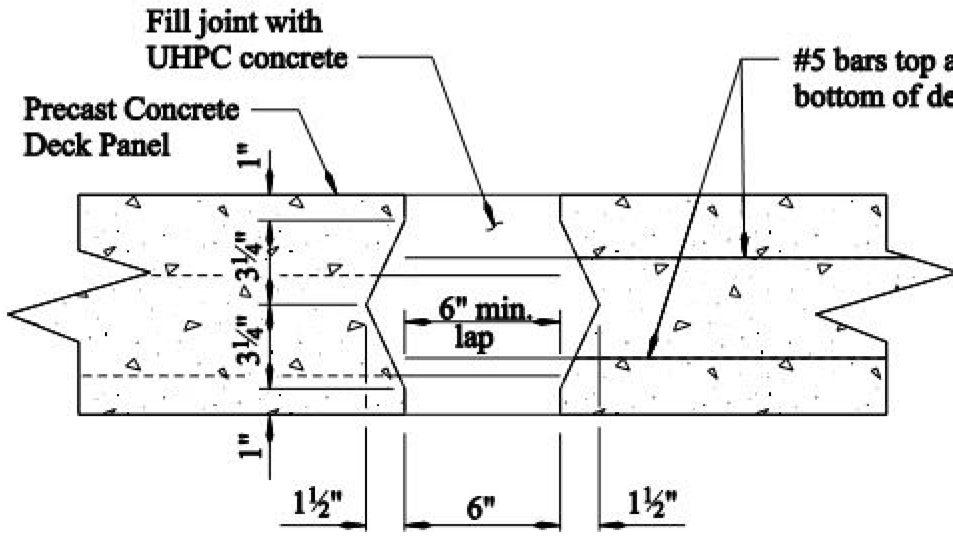

Figure (6) UHPC Connection With Precast Concrete Deck Panel [18]

UHPC will be used in the panel to girder connection shear pockets and built-up haunch sections [18]. Due to the strength properties of UHPC, required surface area for bearing and interface shear, ease of construction and as a cost savings, a haunch width less than the full girder flange width will be used. AASHTO allows for an interface shear reinforcement spacing of up to 4 feet. Currently, Oregon Department of Transportation uses a maximum interface shear reinforcement spacing of 2 feet.

To develop composite action between the precast concrete deck panels and precast concrete girders, uncoated mild steel interface shear reinforcement will be cast in the precast girders in addition to the girder shear stirrups [18]. After erecting the girders and deck panels, the interface shear reinforcement will be field bent to ensure proper alignment within the shear pockets. For traditional cast-in-place decks, the girder shear stirrups are terminated in the monolithically cast deck and haunch. In order to develop the girder shear stirrups below a precast deck, the minimum haunch depth would have to be 6 inches. Furthermore, the spacing of the shear stirrups rarely aligns with the shear blockouts. Therefore, to minimize haunch depth and unnecessary dead load, the girder shear stirrups will be terminated in the girder top flange with hooks as required to develop the reinforcement, as shown in Figure 7.

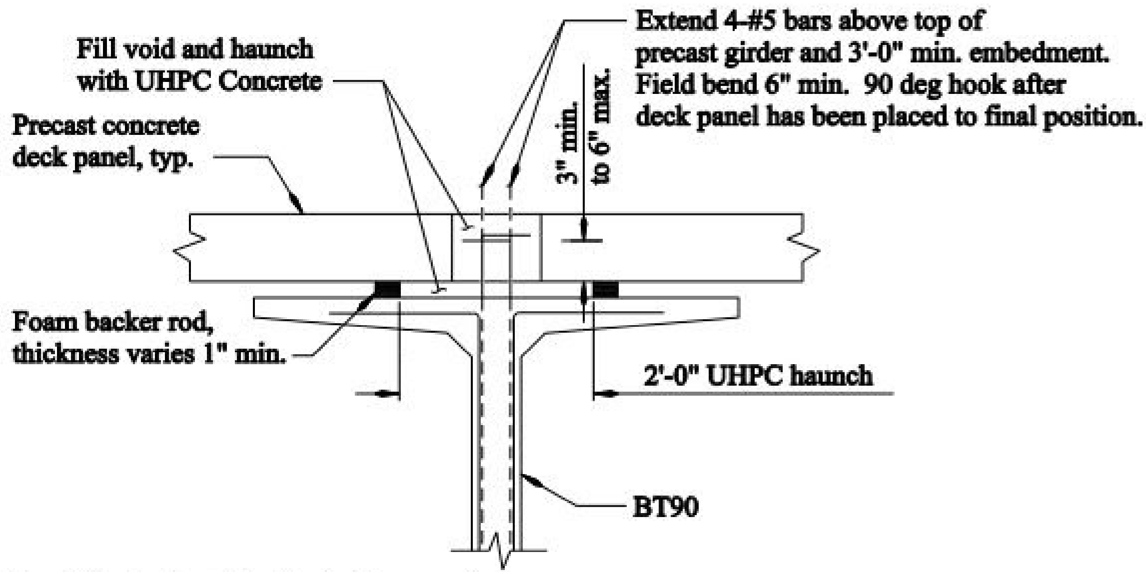

Figure (7) Deck Panel to Girder Connection [18]

Compressible foam backer rods, which are seen in Figure 7 are used to form the haunch sections [19]. Seals based on standard mortar-tight specifications are not adequate to contain and maintain the integrity of the mix. The foam backer rod must form a tight seal to contain the very fluid UHPC mixture. To contain UHPC in areas of superelevation or cross slope, exposed joints and shear pockets require a plywood seal or cover. The plywood cover is installed successively upward from the low point as the UHPC is placed. If plastic coated form grade plywood is used to contain and cover exposed areas of UHPC, no additional measures are required for curing. Curing times vary from three to seven days depending on environmental conditions.

To cast the haunches, UHPC is placed in the shear pockets through a sealed wood chimney or chute that provides approximately one to two feet of static head, as required [19]. With the excellent flow-ability of UHPC no mechanical vibration or pumping is required. To maintain the steel fibers in suspension, vibratory equipment must not be used. Minor rodding of the UHPC can be used in congested areas. Based on UHPC research test samples cast with these methods, annular spaces such as shear pockets and haunches can be completely filled without air voids normally found with traditional grouts.

8. POTENTIAL APPLICATIONS OF UHPC

Different research projects have been conducted to determine if UHPC is suitable for the following applications: drill bits for special foundation engineering, sewer pipes, precast spun columns and poles, barrier walls, field-cast thin-bonded overlays, cable-stayed bridge superstructure, bridge bearings, precast tunnel segments and seismic retrofit of bridge columns. The results of the different research projects indicate that UHPC would be practical in all of these applications. The results of the research projects will be discussed in this section.

8.1 Drill Bits Made With UHPC

The common material for drill bits is steel. Steel is the reference material for possible special foundation applications made of UHPC [20]. There are several fields of special foundation engineering in which steel could be replaced in the future by UHPC. UHPC is characterised by its dense structure, which gives UHPC excellent durability properties. Furthermore, the compression strength of UHPC is about 5 times higher than the compressive strength of conventional concrete. Drill bits are not only applied by compression forces, but also by torque. This makes the shear resistance and shear strength of UHPC extremely important. Hence, shear strength was examined in separate tests.

The use of steel fibers in UHPC compositions leads to greater ductility characteristics than conventional concrete [20]. Hence, steel fibers are also necessary for one-way drill bits made of UHPC. A total failure of the drill bit after stresses reach its strength is prevented by steel fibers limiting the crack width. Drill bits made of UHPC with embedded steel fibers can be characterised by extremely high corrosion resistance. This durability aspect represents a huge advantage for UHPC drill bits over steel bits.

UHPC drill bits were successfully tested at a number of special foundation job sites in Italy and Switzerland [20]. Bored piles with a diameter of 24.2 inches (620 mm) were constructed by using UHPC drill bits. The drilling was completed using the full displacement method in locations with difficult soil conditions. After the drilling process, UHPC drill bits were still fully functional and were free of any cracks. In addition, the essential sealing system between the UHPC drill bit and the drill string remains active so that groundwater from outside cannot flow into the drill string. This ensures that concrete can be poured to construct the foundation. An equivalent drilling performance between UHPC and steel bits was also verified by practical tests. The UHPC drill bit wearing down due to drilling at the surface cannot be avoided, but this does not affect the drilling process.

With the researched drill bit for full displacement piles, a first product made of UHPC is not available [20]. This product may have good market opportunities because of its high quality and proper realisation standard. At the same time, UHPC drill bits are cheaper to produce than steel bits. Technically, UHPC drill bits are not inferior to steel bits. Moreover, the carbon footprint of UHPC drill bits is comparatively small. Economical optimisation in steel fiber content, form and strength improvement will be started in order to achieve market readiness.

8.2 Sewer Pipes

Earth-moist concrete is typically used in the construction of sewer pipes. With the use of a fine-grain and flowable UHPC paste for the creation of earth-moist concrete, specific characteristics of traditional earth-moist concrete can be improved [21]. This includes a denser and more closed surface that is more resistant to external influences. A further increase in efficiency in the production, transportation and handling of the pipes can be achieved by reducing the wall thickness.

The purpose of a research project was to design an earth-moist concrete, which contains a high proportion of coarse grain and a binder paste that is based on a UHPC [21]. The characteristics of this earth-moist concrete should, as with the traditional earth-moist concrete also, be a good green strength immediately after stripping. Furthermore, the results were also evaluated based on the parameters of surface integrity and of dimensional stability of the specimen. In order to achieve these conditions, the optimal relationship between the UHPC and the aggregate has been identified using a vibration proctor test developed by the University of Kassel.

The steel reinforced concrete pipes showed as expected, a much higher crushing strength than the concrete pipes [21]. Results showed the initial cracking during the crushing test of the steel reinforced concrete pipes. For concrete pipes the break would have occurred after the initial crack and this indicates compared to the moist UHPC pipes an increase in the crown compressive strength compared to concrete pipes made out of ordinary earth-moist concrete.

The research showed that the optimal paste content of an earth-moist mixture can be identified using a vibration proctor test [21]. The difference to the original test procedure was that not the water content was increased gradually in the mixture, but instead the UHPC paste was increased gradually. The dense and compact structure of the UHPC paste caused very good compressive strength and crushing results were obtained. Further investigations in this area is necessary to determine the reduction in the wall thicknesses.

8.3 Precast Spun Concrete Columns

In contrast to the mostly flowable consistency of UHPC, spun concrete has to have a soft plastic consistency during placing and a high green strength after the spinning is done [22]. For that reason the content of fine material should be moderate. For the fresh concrete properties as well as the strength the plasticizer is particularly critical. The first trials showed that the so far used plasticizer, on the basis of naphthalene sulfonate, will not achieve the desired result. On the other hand, polycarboxylates, normally recommended to use in UHPC, showed some features, which made them not well suited for spun concrete. Either they led to a flowing but highly viscous mix, which was hard to work with, or the concrete maintained its soft consistency for too long. The latter led to a strong segregation during the spinning process and the liquid cement paste, which slides down and accumulates inside the cavity.

The choice of the plasticizer requires a compromise [22]. The compromise is made by the combination of two polycarboxylates, which have shown the best results so far. The main admixture ensures the optimal liquefaction of the concrete and the other maintains a sufficient workability. The duration of workability can be controlled by means of the ratio of both admixtures. Using standard cement, aggregates and microsilica a mix design was developed and several prototypes were produced. The prototypes produced a concrete mix that exhibited good workability and high performance.

Several test elements and prototypes were made with UHPC [22]. Load tests were performed on columns with different diameters and arrangements of reinforcement. Besides the test elements, prototypes of real columns and poles were made. The five columns have been delivered and assembled on site. The corresponding cube strength ranged between 132.5 and 149.5 N/mm². The compressive strength of cores, taken from one element, was 157.0 N/mm².

These compressive strengths indicated that UHPC could be used for big poles as well, which might lead to thinner wall thicknesses and therefore lighter elements [22]. After a few smaller poles were made, a bigger telecommunication pole was made with UHPC. Four batches of concrete were produced. The average core strength was 172.0 N/mm²

The biggest element made of UHPC was a 26 meter pole for overhead power line [22]. This pole was tested in a bending test. The testing equipment was not able to bend this pole until the failure of the concrete compression zone.

UHPC can be applied for spun concrete. Compressive strength up to 172 N/mm² could be achieved without heat curing and the use of fibers [22]. It could be shown that columns as well as poles can be manufactured without changing the previous production technology. Even elements consisting of several batches could be made.

8.4 Precast Parapets Connected With UHPC

As an alternative to cast-in-place parapets, precast parapets may be supplied to the bridge as separate units to be field attached [23]. The precast parapet units need to become fully composite with the bridge deck system in order to carry the traffic barrier loadings. Field cast UHPC connections for precast parapets and barriers provide the integral continuity and further aids in speeding the construction of the bridge. The gray area in Figure 8 illustrates the UHPC connection between a precast parapet and a bridge deck.

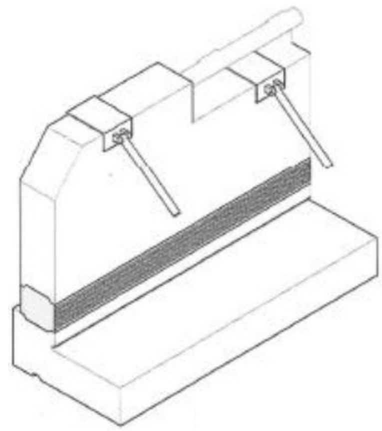

Figure (8) Precast Parapets Connected With UHPC [23]

8.5 Bridge Bearings

For bridge bearings, not only high bearing compression forces need to be transferred, but also movement and rotation need to be allowed [24]. For spherical bearings, significant fabrication effort is necessary for creating the shape in steel. Using UHPC instead of steel may provide significant benefits.

Research was conducted for the design of high performance spherical bridge bearing with UHPC calottes [24]. Substituting steel and hard chromed calottes with sliding lacquer coated UHPC elements can provide a cost effective and favorable process for the production of spherical bearings. The general performance and specific design requirements were analysed in an extensive test program. Suitable performance could be established and proven by full-scale testing. Long term effects such as permanent static load and fatigue loading are not limiting the capacity significantly. Moreover, using UHPC instead of steel avoids corrosion protection problems of the calotte and allows a powerful monitoring system of the bearings load history. Cracks at the calotte can be used as a clear and permanent indicator of overload of the bearing. Such benefits of the bearing comes without compromising load resistance capacity and service performance of the bearing.

8.6 Precast Tunnel Segments

Potential advantages of segmental lining elements made of UHPC are based on the enormous compression strength of approximately 200 MPa [25]. The tensile strength of the uncracked matrix, however, compared to normal strength concrete, increases only sub-proportionally to a value between 7 and 15 MPa. The achievable tensile strength is mainly determined by the fiber content and geometry and also by the distribution of fibers in the material and their compound behavior. Conventional steel fiber reinforced concrete has a fiber content of around 0.5% of total volume, while the fiber content in structural elements made of UHPC rises to 2% of total volume. The use of fibers may substitute conventional steel reinforcement bars and minimize spalling risks and tensile splitting forces.

In addition, ultra high performance concrete shows extraordinary durability properties [25]. The high material density makes UHPC particularly resistant against all kinds of external exposures. Reducing the segment thickness would cause the following economic benefits: reduced excavation diameter and volume, reduced material quantity, reduced transport volume and mass with subsequent reduced construction duration.

Compared to conventional precast reinforced concrete elements of identical geometry, UHPC precast elements show an increased stiffness due to the higher modulus of elasticity [25]. In a research project, the thickness of segments made of UHPC was reduced until the defined deformation limit is reached, thereby decreasing the segment thickness from 0.3 m to 0.22 m which corresponds to about a 25% decrease. The analysis was carried out with non-linear approaches on a partially bedded beam model.

Considering projects with large excavation diameters and segment thicknesses of 0.5 m or more, even higher reduction percentages for segment thicknesses by the use of UHPC can be expected [25]. The rather high material costs may be compensated for by savings in the element production and construction process. The durability of UHPC will also reduce life cycle costs, especially regarding objects built with the single shell lining system. The advantage of the increased load bearing capacity of UHPC elements compared to conventional precast steel reinforced segments may be used in particular where compression forces govern. Therefore smaller diameter tunnels with large overburden or shaft structures will be particularly interesting for further investigations.

8.7 UHPC Piles

The 26 ksi (179 MPa) compressive strength of UHPC is approximately five times that of the normal concrete typically used for pile applications [26]. Since UHPC has greatly improved material strength, sections can be designed with greatly reduced cross-sectional area without compromising pile strength. These reduced sections are then lighter and easier to transport than traditional concrete piles. In fact, a UHPC pile section has a weight approximately equal to a steel pile with a similar capacity. The reduced section allows the UHPC pile to be driven into the ground with less energy than a normal concrete pile. The high strength of UHPC prevents damage during the pile driving process.

UHPC has extremely good durability. The capillary porosity is very low, and the material is extremely resistant to chloride permeability. UHPC experiences virtually no freeze-thaw deterioration even after 800 freeze-thaw cycles [26]. These properties allow the required concrete cover thickness for steel reinforcement to be reduced and thus permit an even further reduction in section sizes for some applications. The excellent durability properties also suggest that UHPC piles may reduce maintenance costs and help extend the lives of some bridges, especially those in harsh environments.

UHPC piles can be successfully cast in a precasting plant as designed [26]. High strengths of 26 to 29 ksi (179 to 200 MPa) are achievable when heat treatment procedures for UHPC are followed. Limited vibration of UHPC piles during casting at locations every five to ten feet along the pile for approximately ten seconds at each location is recommended to eliminate the possibility of forming air pockets in UHPC members.

Researchers studied a 10 by 10-inch (25 by 25-cm) tapered H-shaped UHPC pile section and compared it to a similarly sized HP 10x57 steel pile [26]. The axial load capacity of the UHPC pile was 86% greater than that of the steel pile because of the larger cross-sectional area of the UHPC pile and associated increase in end bearing capacity. This suggests that the use of UHPC piles may reduce the total number of piles required for a typical bridge foundation. The initial cost of a UHPC pile foundation could thus be lower than that of a steel pile alternative in some situations, and the maintenance costs for UHPC piles are expected to be significantly lower than those associated with other types of piles due to the increased durability of UHPC. Somewhat concerningly, one of the UHPC piles failed in shear during the lateral load test, but this was caused by a large bundle of instrumentation wires creating a weak spot in the pile. The UHPC pile used in the field is expected to have a lateral load capacity of 43 kips (191 kN).

The behavior of UHPC piles under thermal cyclic loads should be further researched [26]. Further research would provide engineers with insight on how a UHPC pile would behave in an integral abutment due to the temperature movements of a bridge. If the UHPC piles do not exhibit the progressive cracking damage and section loss that currently prevents normal concrete piles from being used to support integral abutments, then the UHPC piles can be used for integral bridge abutments. However, continuous monitoring would be necessary to confirm the performance of the piles under real cyclic temperature loading. The 10 by 10-inch UHPC pile described above could be installed in a non-integral bridge foundation application without further research, but the performance of the pile even in this condition is worth monitoring to ensure the UHPC pile group behaves as expected.

9. CONCLUSIONS

UHPC can be used as a bridge deck overlay because sufficient bonding to the underlying bridge deck can be achieved. Using UHPC as a bridge deck overlay provides the following benefits: increased durability, reduced cracking and decreased dead load on bridge. The extra cost of UHPC is the biggest factor in this application not being more widely used. In Switzerland, UHPC overlays are being more commonly constructed, and therefore, the costs are becoming more competitive. The cost of a UHPC overlay on the Chillon Viaduct bridge in Switzerland is comparable to the more expensive conventional solutions in the United States.

Adjacent box beam bridges are commonly used in North America for short and medium length bridges, but this bridge design has a common problem, which is the shear key connection deteriorates over time. A partial-depth UHPC connection is sufficient to achieve the performance requirements and is a viable solution for adjacent box beam connections.

UHPC allows for accelerated bridge construction. UHPC has the strength required to connect precast concrete bridge elements together. The use of precast concrete bridge elements is an efficient way to accelerate bridge replacements. So, using UHPC to connect precast concrete bridge elements together can be an invaluable solution when a bridge project needs to be finished on a short schedule.

Generally, using UHPC allows for the design of smaller cross sections than conventional concrete. The steel fibers in UHPC generally provide adequate shear resistance. Hence, the UHPC beams do not contain stirrups normally used in conventional concrete. These benefits provide engineers with more options when designing concrete beams, which can provide an effective solution for certain projects.

Different research projects have been conducted to determine if UHPC is suitable for the following applications: drill bits for special foundation engineering, sewer pipes, precast spun columns and poles, barrier walls, field-cast thin-bonded overlays, cable-stayed bridge superstructure, bridge bearings, precast tunnel segments and seismic retrofit of bridge columns. The results of the different research projects indicate that UHPC would be practical in all of these applications.

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APPENDIX A

Cost Comparison of Overlay Types [4]

Overlay Type	Overlay Thickness, inches (mm)	Cost, $/ft2 ($/m2)
HPC	1–5 (25–127)	17–25 (183–269)
Low slump concrete	1.5–4 (38–102)	13–19 (140–204)
LMC	1–5 (25–127)	18–39 (193–419)
Asphalt with a membrane	1.5–4 (38–102)	3–8 (32–86)
Polymer-based	0.13–6 (3–152)	10–17 (107–183)
Non-proprietary UHPC	1–2 (25–52)	3–6 (32–64)
Proprietary UHPC	1–2 (25–52)	9–18 (97–184)
Rehabilitation of the Chillon Viaduct (Switzerland) using a Proprietary UHPC Overlay	1.6 (40)	20 (215)
Bridge deck replacement	n/a	43–53 (462–570)

APPENDIX B

Completed Projects with UHPC Components [10]

Project	Year	Application
Mars Hill Bridge, Wapello County, IA	2006	Three 45-inch-deep bulb-tee beams
Route 624 over Cat Point Creek, Richmond County, VA	2008	Five 45-inch-deep bulb-tee girders
Jakway Park Bridge, Buchanan County, IA	2008	Three 33-inch-deep pi-shaped girders
State Route 31 over Canandaigua Outlet, Lyons, NY	2009	Joints between deck bulb tees
State Route 23 over Otego Creek, Oneonta, NY	2009	Joints between full-depth deck panels
Little Cedar Creek, Wapello County, IA	2011	Fourteen 8-inch-deep waffle deck panels
Fingerboard Road Bridge over Staten Island Expressway, NY	2011 to 2012	Joints between deck bulb tees
State Route 248 over Bennett Creek, NY	2011	Joints between deck bulb tees
U.S. Route 30 over Burnt River and UPRR bridge, Oregon	2011	Haunch and shear connectors and transverse joints
U.S. Route 6 over Keg Creek, Pottawatomie County, IA	2011	Longitudinal and transverse joints between beams
Ramapo River Bridge, Sloatsburg, NY	2011	Joints between full-depth deck panels
State Route 42 Bridges (2) near Lexington, NY	2012	Joints between full-depth deck panels and shear pockets
State Route 31 over Putnam Brook near Weedsport, NY	2012	Joints between full-depth deck panels
I-690 Bridges (2) over Peat Street near Syracuse, NY	2012	Joints between full-depth deck panels
I-690 Bridges (2) over Crouse Avenue near Syracuse, NY	2012	Joints between full-depth deck panels
I-481 Bridge over Kirkville Road near Syracuse, NY	2012	Joints between full-depth deck panels
Windham Bridge over BNSF Railroad on U.S. Route 87 Moccasin, Montana	2012	Joints between full-depth deck panels and shear connections to beams